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Particle Collection by a Venturi Scrubber Downstream from an Electrostatic Precipitator

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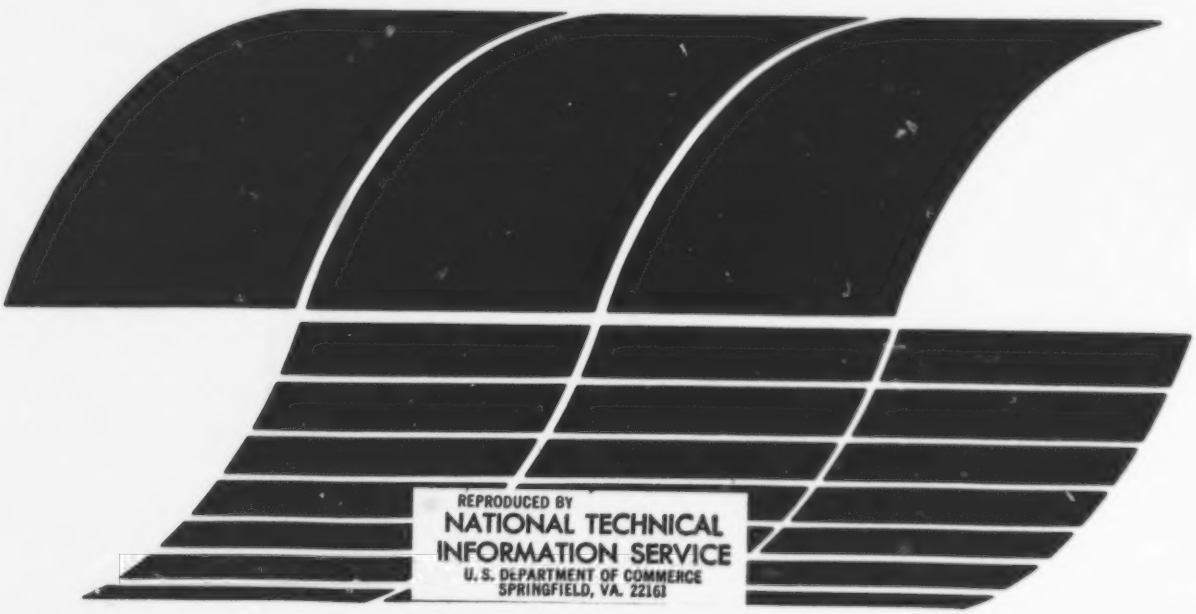
Interagency Energy/Environment R&D Program Report



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ABSTRACT

The results of pilot plant experiments of particulate collection by a venturi scrubber downstream from an electrostatic precipitator (ESP) are presented. The data, which cover a range of scrubber operating conditions and ESP efficiencies, show that particle collection by the venturi scrubber is not affected by the upstream ESP; i.e., for a given scrubber pressure drop, particle collection efficiency as a function of particle diameter is the same for both ESP on and ESP off. The experimental results are in excellent agreement with theoretical predictions. Order of magnitude cost estimates indicate that particle collection by ESP scrubber systems is economically attractive when scrubbers must be used for SO_x control.

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NOMENCLATURE

AC	- Annualized cost, $
C	- Cunningham correction factor
CC	- Capital cost, $
CC_{ESP}	- Capital cost of ESP, $
$CC_{scrubber}$	- Capital cost of scrubber, $
d	- Particle diameter, μm
d_A	- Aerodynamic particle diameter, μmA
E	- Fan efficiency
H	- Number of operating hours per year
I	- Intensity of light transmitted through aerosol
I_o	- Intensity of light source
K	- Light scattering parameter, cm^3/m^2
K_e	- Cost of electric power, $/kW-hr
L	- Optical path length
L/G	- Liquid to gas flow rate ratio, m^3/m^3
Pt_{ESP}	- Overall penetration through ESP
Pt_{ESPS}	- Overall penetration through ESP scrubber
$Pt(d)_{ESP}$	- Penetration of particles with diameter d through ESP
$Pt(d)_{ESPS}$	- Penetration of particles with diameter d through ESP scrubber
$Pt(d)_s$	- Penetration of particles with diameter d through scrubber
Q	- Flow rate, m^3/hr
r_{gw}	- Geometric mass mean particle radius
SCA	- Specific collector area, $m^2/Am^3/s$
SCA_{min}	- Minimum specific collector area, $m^2/Am^3/s$
W	- Mass concentration of particles
ΔP	- Pressure drop, cm of water
ρ	- Density, g/cc
σ_g	- Geometric standard deviation

INTRODUCTION

There is considerable interest in using electrostatic precipitator (ESP) scrubber systems for particulate collection in coal fired utility boilers. At least one utility plans to use a moderately efficient ESP followed by a scrubber to meet emission standards for a new boiler. The recent amendments to the Clean Air Act which require SO_x removal for most plants are likely to increase interest in ESP scrubber systems.

There are numerous undocumented reports that a scrubber downstream from an ESP works better than expected. Theoretical and experimental studies of particle collection by drops indicate that there is no reason to expect a scrubber downstream from an ESP to have different performance characteristics than a scrubber alone.[1] But data on ESP scrubber combinations are insufficient to allow one to determine if the results from drop collection theory apply to scrubbers.

The experimental study discussed in this report was undertaken to provide the necessary data. Also a theoretical study was conducted to determine what ESP scrubber configurations are capable of meeting the possible particulate New Source Performance Standard for utility boilers of 13 ng/J (0.03 lb/10^6 Btu). Order of magnitude cost estimates were also made.

The objectives of the program were to:

1. Determine the effect of an ESP on the particle penetration (1 minus efficiency) of a venturi scrubber as a function of particle diameter characteristics.

2. Determine the overall mass penetration and particle penetration as a function of particle diameter for the ESP scrubber system.

3. Determine, with the aid of mathematical models, the ESP scrubber configurations capable of meeting an emission standard for fly ash of 13 ng/J.

4. Estimate order of magnitude costs for the systems in 3 above.

CONCLUSIONS

The results of the experimental and theoretical studies support the following conclusions:

1. The performance of a venturi scrubber is not affected by the ESP; i.e., the particle penetration versus particle diameter characteristics of the scrubber are the same whether the ESP is on or off.

2. The performance of the scrubber is adequately modeled by the SR-52 programmable calculator model described by Sparks.[2]

3. An ESP scrubber system can achieve an emission of 13 ng/J.

4. Annualized costs of an ESP scrubber system are attractive when compared to costs for an ESP alone for many cases.

5. Plume opacity from an ESP scrubber system may be much higher for a given mass emission than the plume opacity from an ESP alone.

RECOMMENDATIONS

1. Detailed cost studies of ESP scrubber sytems should be conducted to determine their economics.

2. Experimental and theoretical studies of plume opacity from ESP scrubber systems should be undertaken.

EXPERIMENTAL EQUIPMENT

The scrubber system tested in conjunction with the ESP system consisted of a venturi scrubber, an entrainment separator, and a blower and motor. The venturi scrubber had a round cross section with a throat length of 25.4 cm. The throat section could be removed so various throat diameters could be tested. The ESP scrubber tests involved only two throat diameters: 7.62 and 10.16 cm. Larger diameters could not be installed due to the limiting size of the opening at the throat bottom flange. The water was added tangentially at two points at the top of the scrubber. The water flow rate could be varied up to a maximum of 6.43×10^{-2} m^3/min. The scrubbing water was not recirculated. Maximum gas flow was about 28 m^3/min.

Following the venturi scrubber, the gas stream entered a cyclonic entrainment separator. The separator had a diameter of 50.8 cm and was 1.22 m in height. The gas entered the separator at the bottom and exited tangentially near the top. The gas was moved through the system by a blower powered by a 15 hp motor.

The installation of the scrubber to the outlet of the ESP involved removing a 3 m section of duct from the ESP system and rerouting the gas stream through the scrubber system and back to the original ESP system duct, as shown in Figure 1. A transition section was added to the ESP duct to reduce the duct diameter from 30.48 to 15.24 cm to accommodate the scrubber. Flexible duct was used to connect the transition section to the scrubber. The gas was exhausted from the entrainment separator through a 15.24 cm duct to the fan and through a flexible duct (30.48 cm diameter) to connect the fan to the original ESP exhaust system.

Pressure taps were added to the duct at the entrance to the scrubber, between the scrubber and separator, and at the exit of the separator. The pressure taps allowed for measurement of pressure drop over the scrubber and separator.

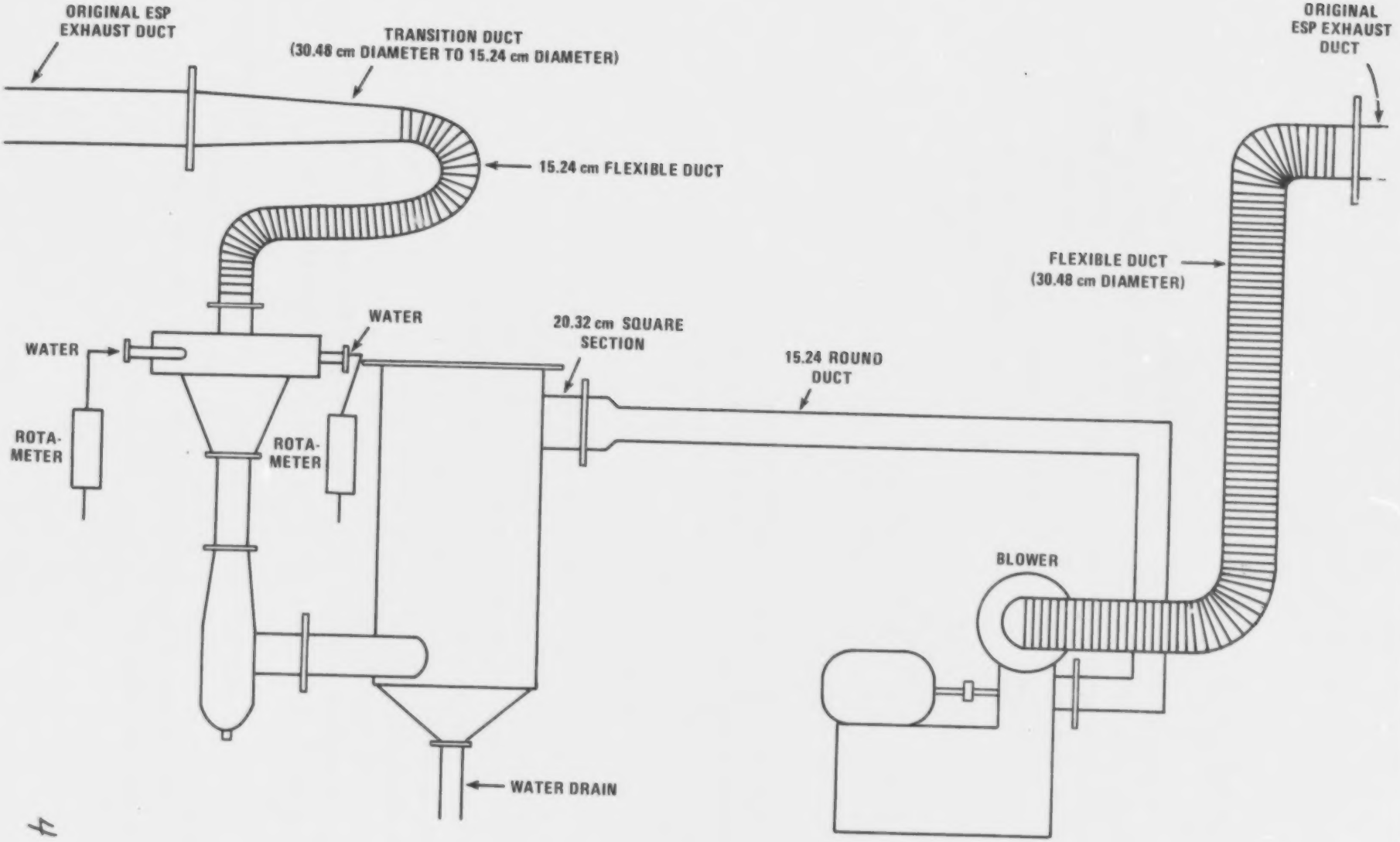

Figure 1. Scrubber system added to ESP outlet.

The ESP used for the experiment is a one lane wire duct ESP and is fully described by Lawless et al.[3]

The aerosol generator consisted of two sand blast guns which were fed fly ash by a vibrating screw feeder. Preliminary experiments were conducted with fly ash fed directly to the sand blast guns. These experiments showed that significant fly ash settled in the inlet duct. A cyclone was placed in the line between the feeder and the sand blast guns, to prevent dust fallout in the inlet duct. Previous experience showed that this aerosol generator was stable. Additional information can be found in Lawless et al. The particle size distribution was approximately log-normal with a geometric mass mean diameter of about 5.5 μmA and geometric standard deviation of 2.3 when the cyclone was used.

All size distribution measurements were made with Meteorology Research, Inc. (MRI) cascade impactors with greased substrates. The impactors were calibrated by personnel of EPA Industrial Environmental Research Laboratory's Particulate Technology Branch (PATB), using the procedure described by Calvert et al.[4]

TEST PROGRAM

The experimental program was divided into two phases: Phase 1 was a preliminary study, and Phase 2 was a systematic study with replication.

The variables studied in the Phase 2 experiments were:

ESP on or off
ESP penetration 1 to 0.037 (efficiency 0 to 96.3%)
Liquid/gas ratio 6.65×10^{-4} to 2.66×10^{-3} m^3/Am^3

The experimental conditions for all tests are shown in Table 1.

EXPERIMENTAL RESULTS

The overall penetrations for the ESP, the scrubber and the ESP scrubber system are shown in Table 1. Since the particle size distribution

Table 1. EXPERIMENTAL CONDITIONS FOR ESP SCRUBBER EXPERIMENTS

Date	ESP Penetration	Scrubber Parameters				Overall Penetration for System
		Throat Diameter, cm	L/G, m^3/m^3	ΔP, cm H_2O	Penetration	
12/17/77	0.05	10.16	1×10^{-3}	31.1	0.0226	0.00113
12/18/77	ESP off	10.16	1×10^{-3}	31.1	0.022	0.022
12/19/77	0.034	10.16	1×10^{-3}	31.1	0.024	0.000816
1/16/78	0.382	10.16	1.2×10^{-3}	39.6	0.0129	0.0049
1/17/78	0.34	10.16	1.2×10^{-3}	39.6	0.0165	0.0056
1/19/78	ESP off	10.16	1.2×10^{-3}	39.6	0.0106	0.0106
1/23/78	ESP off	10.16	1.2×10^{-3}	39.6	0.010	0.010
1/24/78	ESP off	10.16	2.3×10^{-3}	68.3	0.0022	0.0022
1/25/78	ESP off	10.16	2.3×10^{-3}	68.3	0.0020	0.0020
1/26/78	0.328	10.16	2.3×10^{-3}	68.3	0.0034	0.0011
1/27/78	0.516	10.16	2.3×10^{-3}	68.3	0.004	0.0021
2/3/78	ESP off	7.62	1.2×10^{-3}	62.2	0.0041	0.0041
2/6/78	ESP off	7.62	1.2×10^{-3}	62.2	0.0048	0.0048
2/7/78	0.257	7.62	1.2×10^{-3}	62.2	0.0072	0.0018
2/8/78	0.256	7.62	1.2×10^{-3}	62.2	0.0079	0.0020
2/14/78	ESP off	10.16	5.32×10^{-4}	26.7	0.0235	0.0235
2/15/78	ESP off	10.16	5.32×10^{-4}	26.7	0.019	0.019
2/21/78	0.733	10.16	5.32×10^{-4}	26.7	0.0138	0.010
2/23/78	0.0375	10.16	5.32×10^{-4}	26.7	0.0911	0.0034

into the scrubber depends on the penetration through the ESP, the overall penetration results shown in Table 1 must not be used to determine the effect of the ESP on scrubber performance. Instead, the particle penetration as a function of particle diameter (the graded penetration) curves for the scrubber must be used to determine the effect of the ESP. (The graded penetration curve for a scrubber is independent of the inlet particle size distribution.)

The graded penetration curves for Phase 1 are shown in Figure 2 as a plot of penetration versus aerodynamic particle diameter, d_A. ($d_A = d\sqrt{\rho C}$ where d is the physical particle diameter, ρ is the density of the particle, and C is the Cunningham correction factor.) The predicted graded penetration curve is also shown in Figure 2.

The results of all the Phase 2 tests are shown in Figure 3. The average graded penetration curves for each of the Phase 2 tests are shown in Figure 4.

It is obvious from the data shown in Figures 2 and 4 that scrubber performance is dominated by the pressure drop across the scrubber and that the ESP has no effect on the performance of the scrubber. It is also clear from Figure 2 that the predicted graded penetration curve is in excellent agreement with the experimental data.

Statistical analysis of the data showed that:

1. There was no effect on scrubber performance due to the ESP.

2. Particle collection in the venturi was dominated by pressure drop.

3. Changes in throat diameter (i.e., changes in gas velocity in the throat) had more effect than changes in L/G.

4. The estimated standard deviation in the experimental graded penetration curves was about 20%.

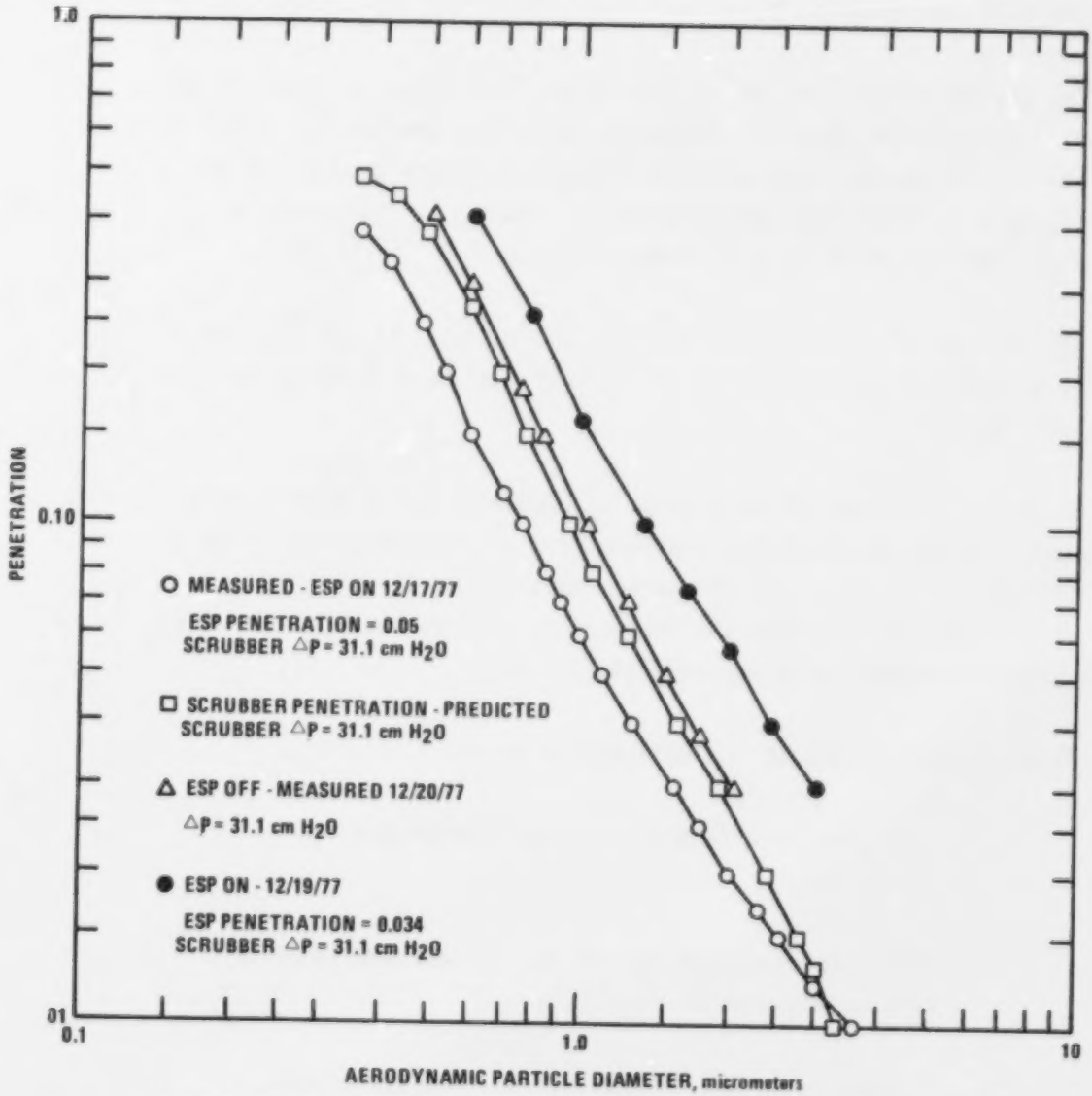

Figure 2. Graded penetration curves for venturi scrubber - phase 1 experiments.

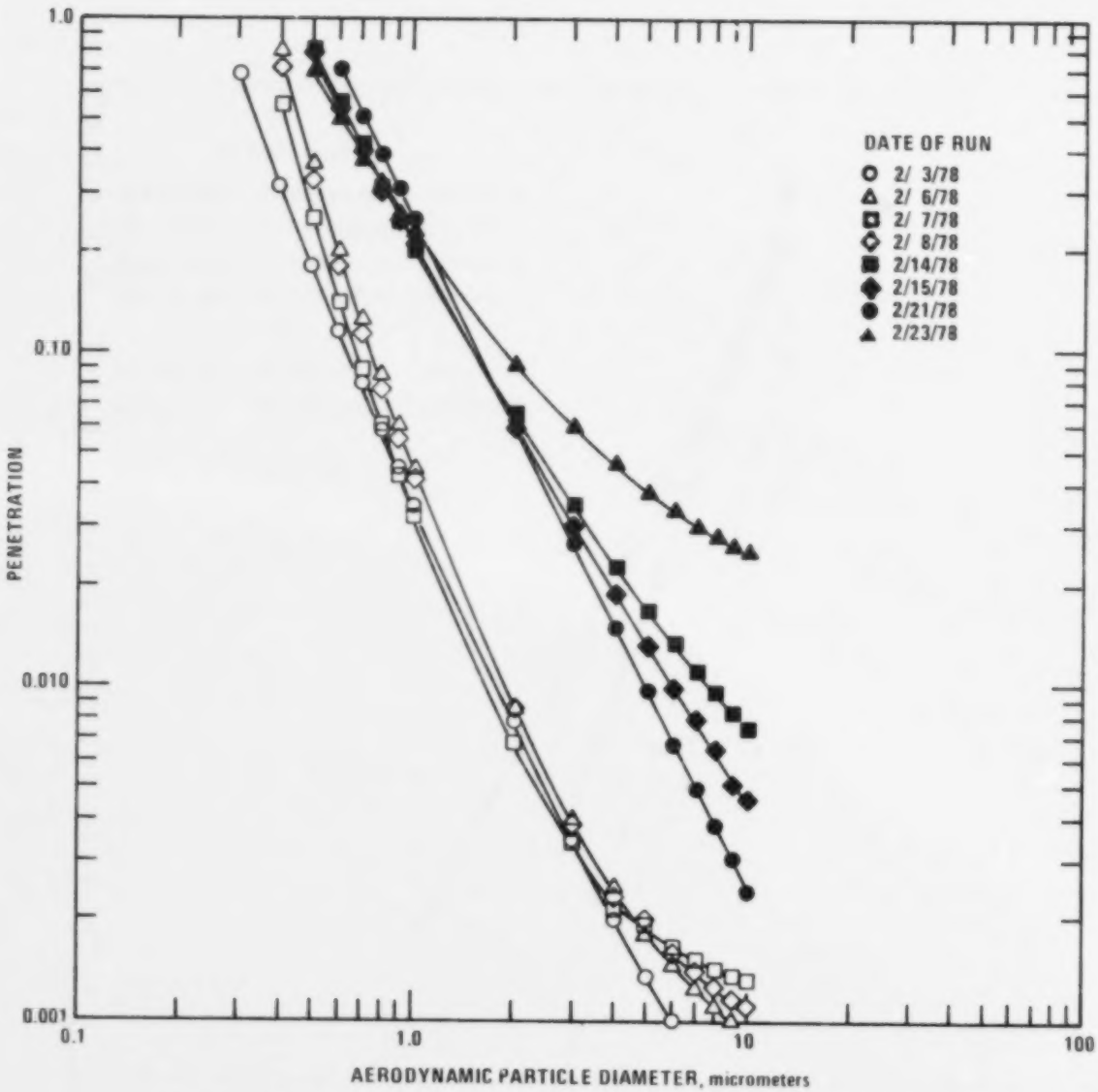

Figure 3. Graded penetration curves for venturi scrubber - phase 2 experiments.

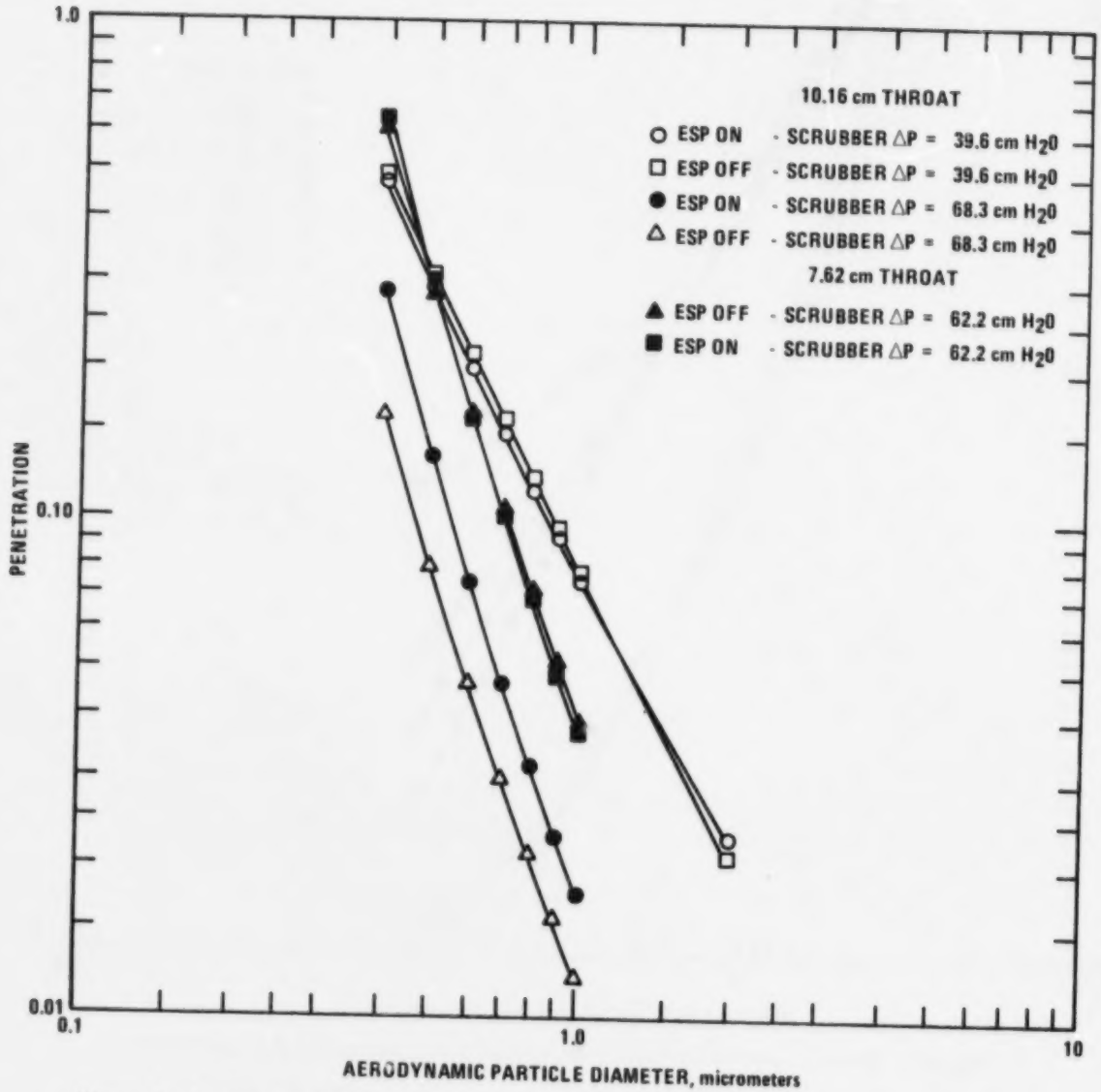
1.0
0.10
0.01
0.1
1.0
10
PENETRATION
AERODYNAMIC PARTICLE DIAMETER, micrometers
10.16 cm THROAT
ESP ON - SCRUBBER ΔP = 39.6 cm H2O
ESP OFF - SCRUBBER ΔP = 39.6 cm H2O
ESP ON - SCRUBBER ΔP = 68.3 cm H2O
ESP OFF - SCRUBBER ΔP = 68.3 cm H2O
7.62 cm THROAT
ESP OFF - SCRUBBER ΔP = 62.2 cm H2O
ESP ON - SCRUBBER ΔP = 62.2 cm H2O

Figure 4. Average graded penetration curves for venturi scrubber - phase 2 experiments.

ESP Scrubber System Performance

The overall mass penetration of the ESP scrubber system for each run is summarized in Table 1. Note that in all cases the overall mass penetration is quite low; i.e., the overall mass collection efficiency is quite high.

Typical graded penetration curves for the ESP scrubber system are shown in Figures 5 and 6. These curves indicate that the ESP scrubber system is capable of meeting the proposed revised New Source Performance Standard. In other words, a particle collection system operating with the characteristics shown in Figures 5 and 6 can collect fly ash with a typical size distribution with penetrations less than 0.003 (efficiencies greater than 99.7%).

THEORETICAL ANALYSIS OF COMBINED ESP SCRUBBER SYSTEMS

The data presented in previous sections clearly show that particle collection by a scrubber is adequately modeled by Calvert's venturi scrubber model. ESP particle collection data show that the EPA/SoRI ESP model[5] adequately predicts ESP performance. Therefore, the performance of a combined ESP scrubber system should be adequately predicted by a combination of the two models.

The predictions of the two models were combined to obtain order of magnitude estimates of the performance and economics of using an ESP scrubber system as opposed to either an ESP or a scrubber alone. In essence such a system represents a tradeoff between scrubber pressure drop and ESP plate area.

Two cases were examined:

- A low current density case which corresponds to a fly ash with high electrical resistivity ($\sim 5 \times 10^{11}$ ohm cm) such as produced by low sulfur coal (<1% S).

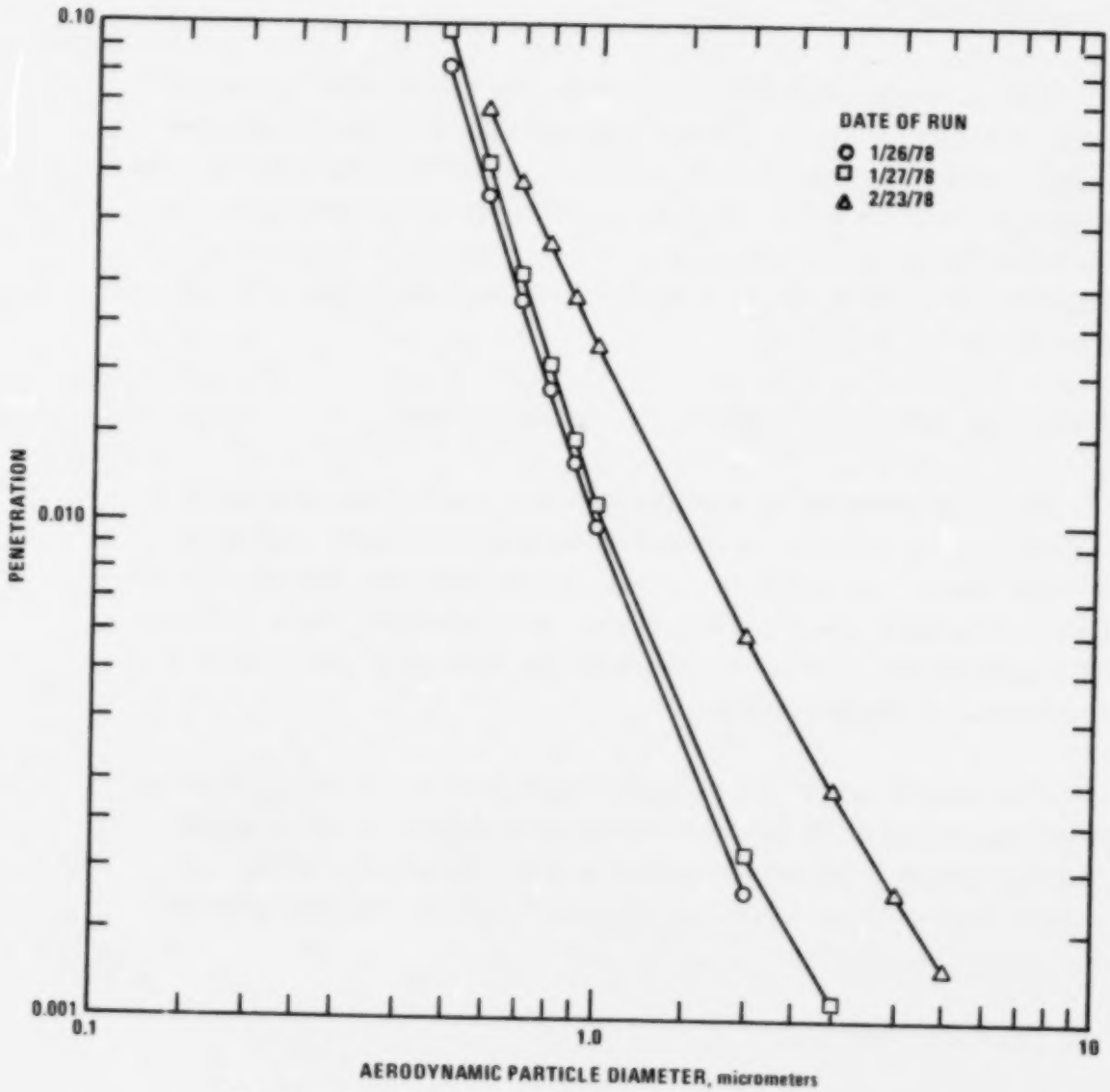

Figure 5. Graded penetration curves for the ESP scrubber system.

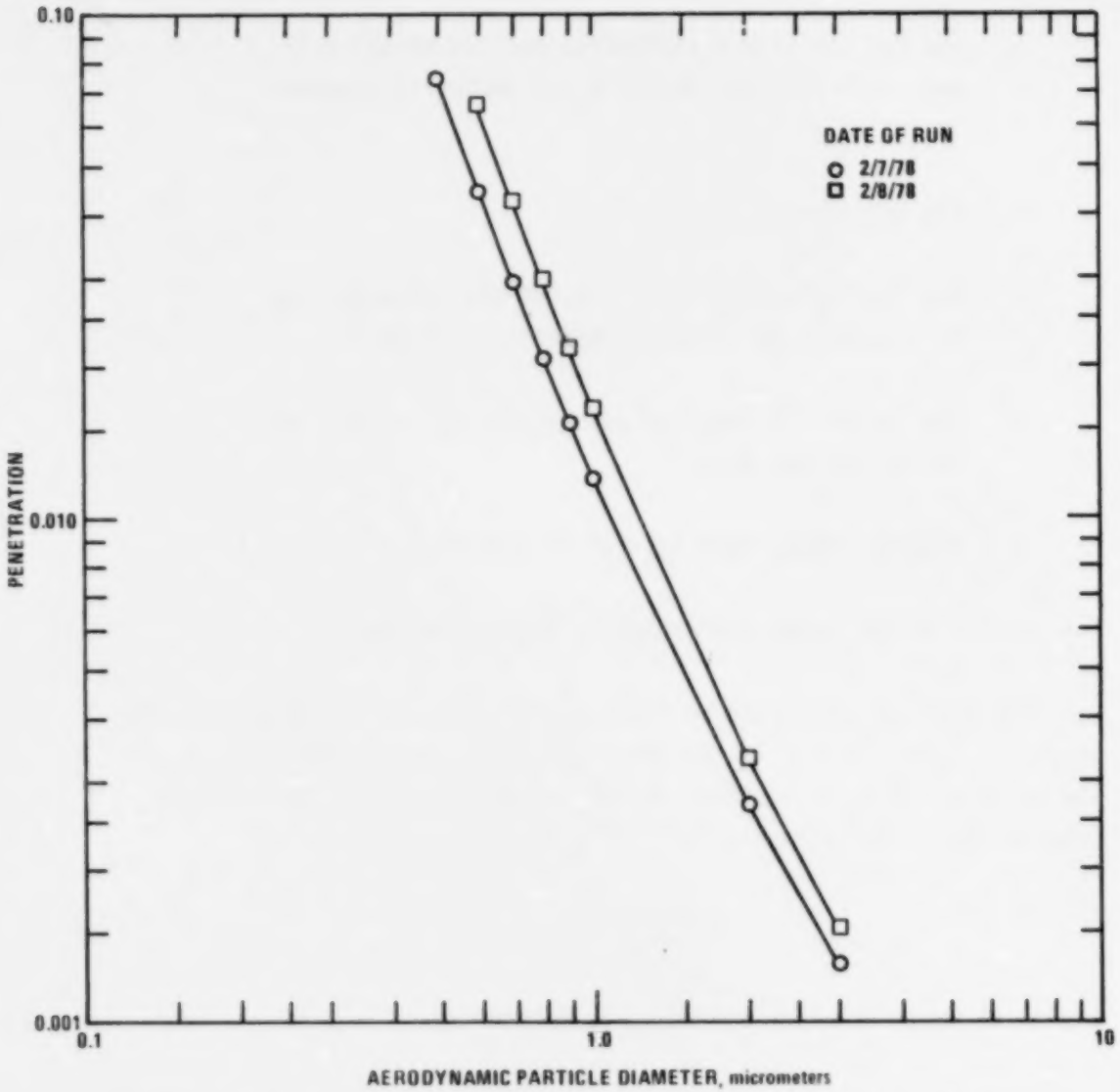

Figure 6. Graded penetration curves for the ESP scrubber system.

- A moderate current density case which corresponds to a fly ash with moderate electrical resistivity ($\sim 3 \times 10^{10}$ ohm cm) such as produced by moderate sulfur coals ($\sim$1.5-2% S).

The following assumptions were made:

1. The fly ash size distribution was log-normal with mass mean diameter of 20 μm and geometric standard deviation of 4.5.

2. Fly ash density was 2.4 g/cc.

3. Gas flow distribution in the ESP was characterized by a normalized standard deviation of 0.25.

4. The factor for sneakage and nonrapping reentrainment in the ESP was 0.1.

5. Rapping losses were typical as described by McDonald.[5]

The results of the calculations are summarized in Table 2.

The results summarized in Table 2 show that the scrubber pressure drop, ΔP, is a function of the penetration through the ESP, $\overline{Pt}_{ESP}$, and is essentially independent of the current density. The pressure drop to $\overline{Pt}_{ESP}$ relationship is:

$$\Delta P = 85\ \overline{Pt}_{ESP} \qquad (1)$$

where ΔP is in cm water and $\overline{Pt}_{ESP}$ is a fraction.

Because the specific collector area, SCA, required to give a given $\overline{Pt}_{ESP}$ is a function of the current density, the relationship between ΔP and SCA is different for the two current densities:

Table 2. SUMMARY OF CALCULATED RESULTS FOR ESP SCRUBBER SYSTEM

Configuration ID Number	ESP Parameters SCA $m^2/Am^3/s$	$\overline{Pt}$	Resistivity	Scrubber Parameters P cm water	$\overline{Pt}$	Overall Penetration
1	156.1	0.0024	high	-	-	0.0024
2	78.04	0.0165	"	9.1	0.182	0.003
3	33.93	0.0771	"	24.0	0.0389	0.003
4	16.43	0.187	"	34	0.016	0.003
5	8.214	0.330	"	43	0.009	0.003
6	74.32	0.002	moderate	-	-	0.002
7	35.47	0.0164	"	8	0.183	0.003
8	15.30	0.0762	"	24	0.0394	0.003
9	7.094	0.186	"	34	0.016	0.003
10	3.393	0.331	"	43	0.0091	0.003
11	0	-	-	67	0.0029	0.003

- For the high current density case,

$$\Delta P = \exp (3.94 - 0.0536\ SCA) \quad (2)$$

- For the low current density case,

$$\Delta P = \exp (3.90 - 0.0220\ SCA) \quad (3)$$

For both, P is in cm water and SCA is in $m^2/Am^3/s$.

The calculated results show that the SCA can be reduced by about a factor of 2 for both moderate and high resistivity cases, for a scrubber ΔP of about 10 cm water.

DISCUSSION

The initial reaction to the calculated and experimental results is one of disbelief. It does not appear reasonable to expect a fairly inefficient ESP and a moderate to low pressure drop scrubber to perform as well as both the experimental data and the calculated results show. An examination of the particle penetration versus particle diameter curves (the graded penetration curve) for both devices acting alone and the combined graded penetration curve can explain the results.

The calculated graded penetration curve for an ESP with a penetration of 0.0771 is shown in Figure 7. Note that the ESP curve has a broad peak from about 0.4 to 1 μm and then drops fairly rapidly on both sides of the peak. On the other hand the graded penetration curve, Figure 8, for a scrubber needed to produce an emission of 13 ng/J in combination with the ESP drops rapidly from essentially 1.0 at 0.1 μm to less than 0.01 at 3 μm. The scrubber is seen to be efficient in particle diameter regions where the ESP is inefficient and the ESP is efficient in particle diameter regions where the scrubber is inefficient. The two devices complement each other.

The graded penetration of the ESP scrubber system can be obtained by multiplying the two separate graded penetration curves; i.e,.

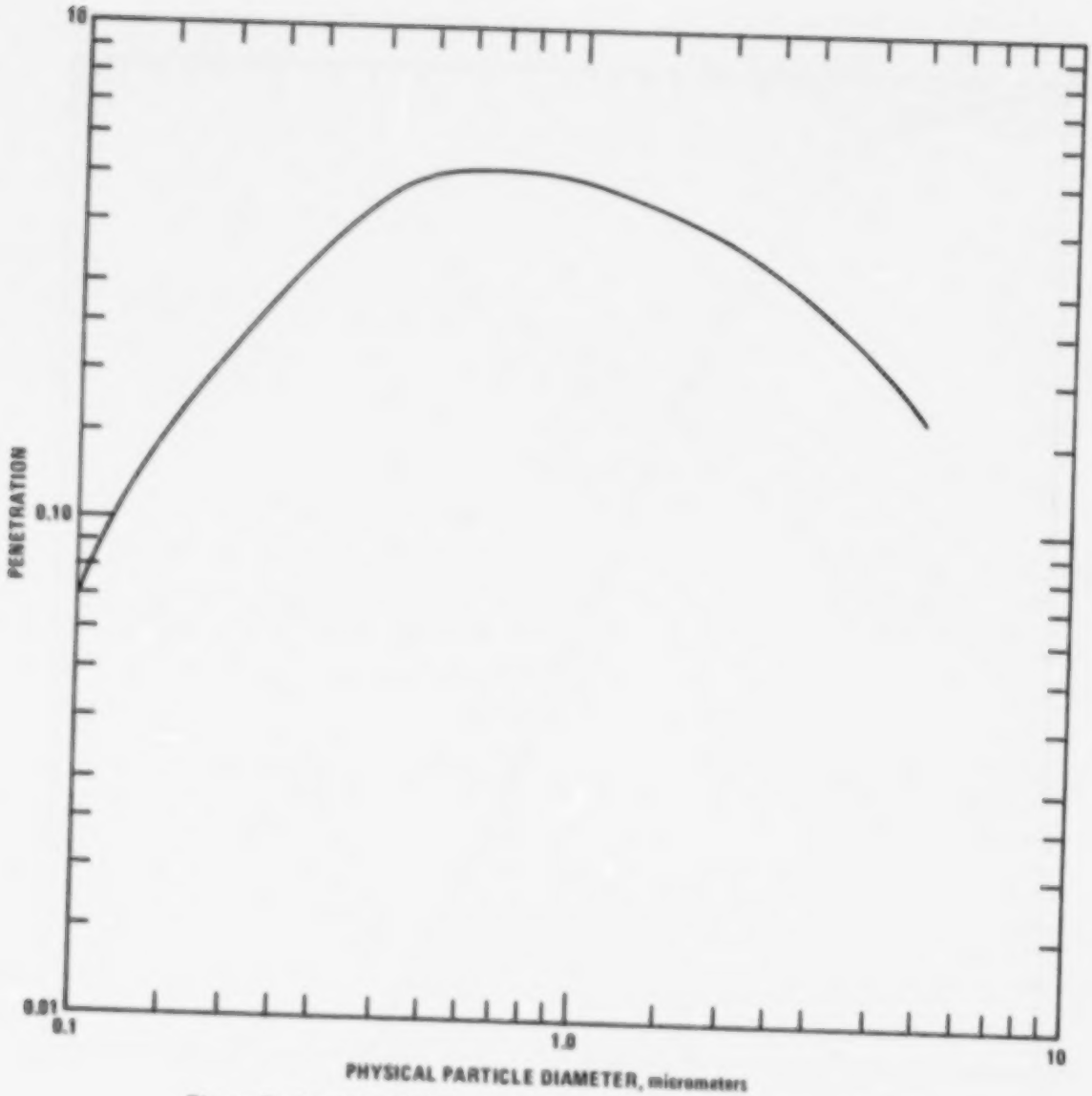

Figure 7. Graded efficiency curve for ESP with penetration of 0.0771.

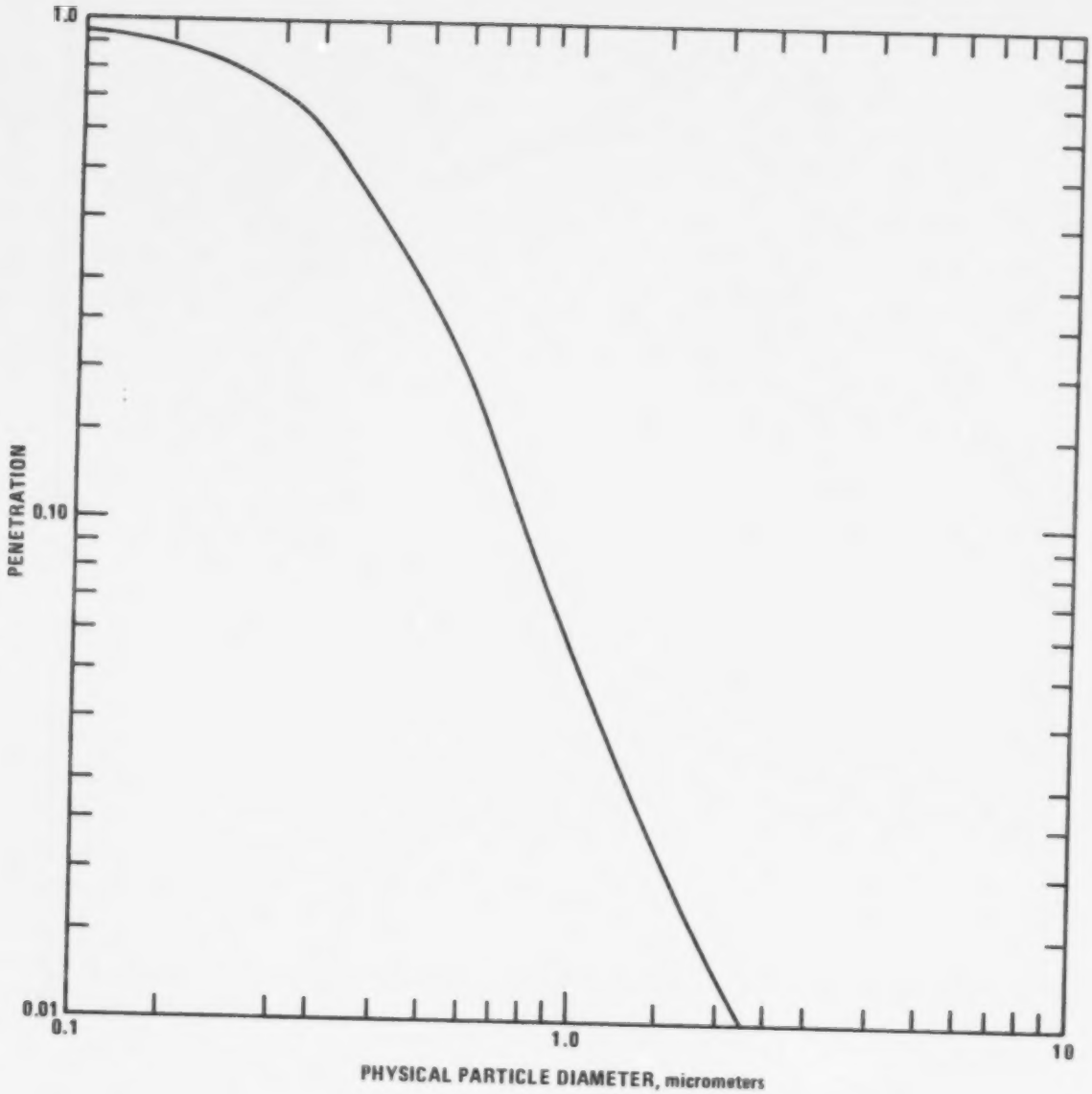

Figure 8. Penetration versus particle diameter for scrubber with pressure drop = 23 cm H_2O, density - 2.4 g/cc.

$$Pt(d)_{ESPS} = Pt(d)_{ESP} \times Pt(d)_{S} \quad (4)$$

where

$Pt(d)_{ESPS}$, $Pt(d)_{ESP}$ and $Pt(d)_{S}$ are the penetrations of particles with diameter d for the ESP scrubber system, the ESP alone, and the scrubber alone, respectively. The resulting graded penetration curve is shown in Figure 9. Note the curve has a sharp peak at about 0.3 μm and drops rapidly on both sides. This sharp peak is characteristic of the ESP scrubber system and, as is discussed in the section on plume opacity, may cause problems with respect to plume opacity limits. (Note that the curves in Figures 7, 8, and 9 are for penetration versus physical particle diameter, not aerodynamic particle diameter as in Figures 2, 3, 4, 5, and 6.)

The experimental graded penetration curves for the ESP scrubber system do not show the peak in penetration because data for particle diameters less than about 0.7 micrometers are not available.

COST ANALYSIS

A detailed cost analysis is necessary to determine if the trade off between pressure drop and SCA is justified.

The order of magnitude cost analysis involves the following assumptions:

1. The total turnkey capital cost of a cold-side ESP is $\$30/m^2$ plate area. (A rough range of total turnkey cost is \$270 to \$370 per m^2.)

2. There is no capital cost of the scrubber because it is needed for SO_x control.

3. Fan efficiency is 60%.

4. Electricity cost is \$0.03/kW hr.

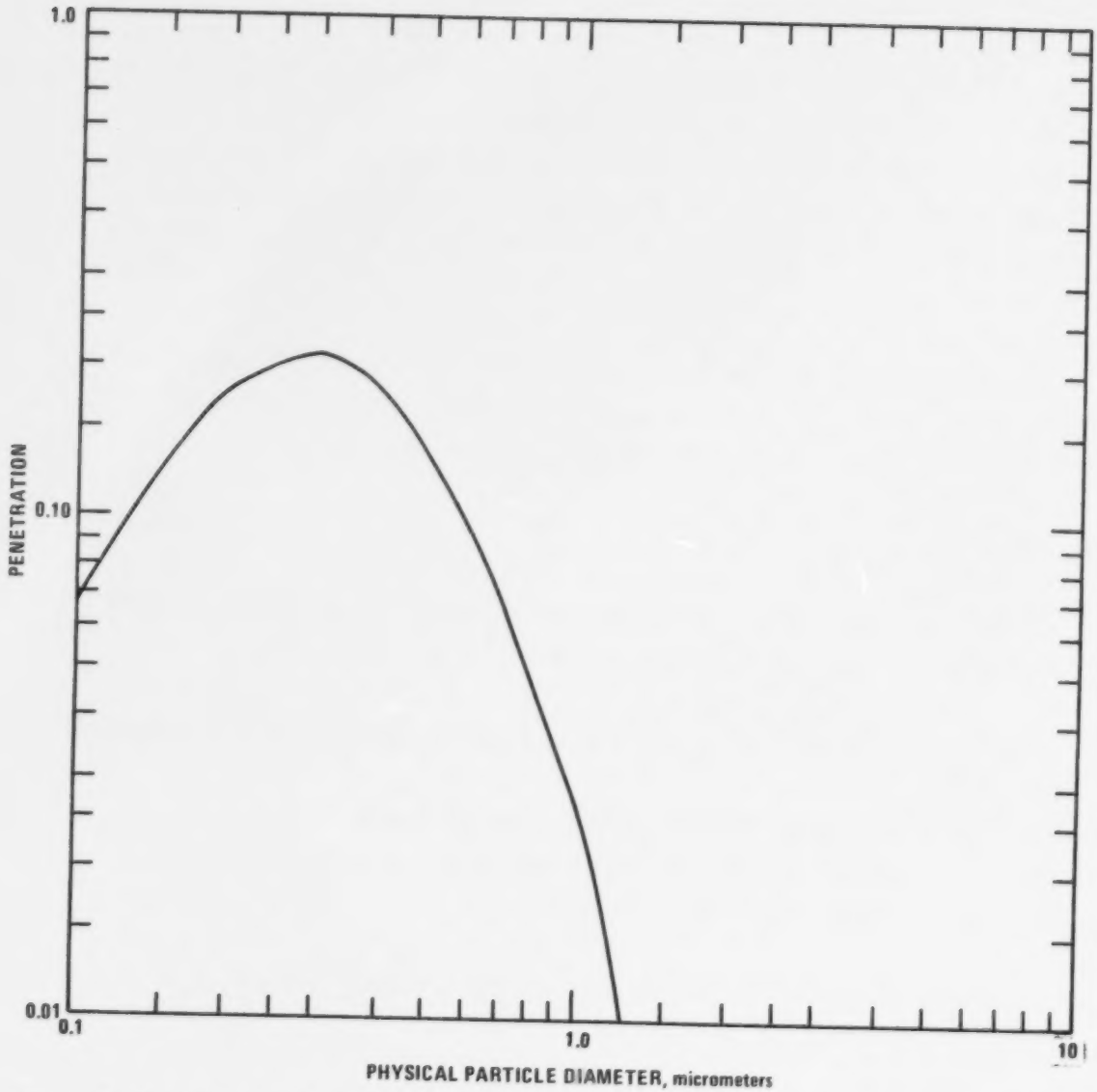

Figure 9. Graded penetration curve for ESP scrubber system - ESP penetration = 0.0771 scrubber pressure drop = 23 cm H_2O.

5. Annualized capital charges are 15% of total turnkey capital cost.

6. Plant operates 6100 hrs per year (~70% capacity).

7. ESP operating and maintenance costs are insignificant compared with capital costs of ESP and can be neglected.

8. Scrubber maintenance and liquid loop costs are not included because they are needed for the SO_x system.

9. Costs are for 1 MW which produces 5440 Am^3/hr of flue gas.

With these assumptions the total annualized cost per MW is given by:

$$AC = Q \left[4.38 \times 10^{-3} HK_e \frac{\Delta P}{15.8E}\right] + 0.15\ CC \qquad (5)$$

where AC is the annualized cost
Q is the flow rate in Am^3/hr,
H is the number of operating hours per year
K_e is the cost of electric power in $ per kW hr
ΔP is the scrubber pressure drop in cm H_2O
E is the fan efficiency
CC is the capital cost in $
4.38×10^{-3} and 15.8 are unit conversion constants

For a 1 MW plant:

$Q = 5440\ Am^3/hr$
$H = 6100$
$K_e = \$0.03$
$E = 0.60$
$CC = \frac{320 \times SCA \times Q}{3600}$

where SCA is the specific collector area in $m^2/Am^3/sec$, and 3600 is necessary to convert Am^3/hr to Am^3/sec.

For the moderate resistivity case

$$\Delta P = \exp (3.94 - 0.0536\ SCA)$$

and for the high resistivity case

$$\Delta P = \exp (3.90 - 0.022\ SCA)$$

The cost equation for the moderate resistivity case is:

$$AC = 5440 \left\{ \left[\frac{4.38 \times 10^{-4} \times 6100 \times 0.03 \exp (3.94 - 0.0536)}{15.8 \times 0.6} \right] + \frac{0.15 \times 320}{3600} SCA \right\} \quad (6)$$

The SCA for minimum cost can be obtained from dAC/dSCA = 0. For the moderate resistivity case:

$$\frac{dAC}{dSCA} = 5440 \left[8.46 \times 10^{-3} \exp (3.94-0.0536\ SCA) \times -0.0536 + 1.33 \times 10^{-2} \right]$$

$$= 4.53 \times 10^{-4} \exp (3.94 - 0.0536\ SCA) + 1.33 \times 10^{-2} = 0 \quad (7)$$

$$4.53 \times 10^{-4} \exp (3.94 - 0.0536\ SCA) = 1.33 \times 10^{-2} \quad (8)$$

$$3.94 - 0.0536\ SCA_{min} = \ln \left(\frac{1.33 \times 10^{-2}}{4.53 \times 10^{-4}} \right) \quad (9)$$

$$SCA_{min} = \frac{3.94 - \ln 29}{0.0536} \quad (10)$$

$$= 10.7\ m^2/Am^3/sec$$

For the high resistivity case the only change is in the exponential term and

$$SCA_{min} = \frac{3.90 - \ln 71.4}{0.022} = -0.37\ m^2/Am^3/sec \quad (11)$$

In other words the scrubber alone is the minimum cost option. The cost for the moderate resistivity case is:

$$\$2.1 \times 10^3/\text{year/MW}$$

The cost for the high resistivity case is

$$\$2.3 \times 10^3/\text{year/MW}$$

The maximum cost for the high resistivity case is for the ESP alone and is $\$11 \times 10^3$/year/MW. The maximum cost for the moderate resistivity case is also for the ESP alone and is $\$5 \times 10^3$/year/MW.

The cost picture is changed somewhat if a scrubber has to be purchased for particulate removal. In this case Equation 6 becomes

$$AC = 5440 \left[8.46 \times 10^{-3} \exp (3.94 - 0.0536\ SCA) + 1.33 \times 10^{-2}\ SCA \right] + 0.15\ CC_{scrubber} \quad (12)$$

for the moderate resistivity case and

$$AC = 5440 \left[8.46 \times 10^{-3} \exp (3.90 - 0.022\ SCA) + 1.33 \times 10^{-2}\ SCA \right] + 0.15\ CC_{scrubber} \quad (13)$$

for the high resistivity case. $CC_{scrubber}$ is the capital cost of a scrubber. Ensor et al.[6] reported that the turnkey capital cost of a particulate scrubber system is \$50/kW or \$50,000/MW. The annualized cost of the scrubber is 0.15 x \$50,000 = \$7,500 which must be added to the minimum costs calculated earlier. The annualized cost for the moderate resistivity cases becomes \$9,600 per MW per year, which exceeds the cost of ESP alone. The annualized cost for the high resistivity case becomes \$9,800/MW/year which is still less than the cost of the ESP alone.

It must be noted that the cost calculations above are based on general cost data which have a great deal of uncertainty in them. However, the cost calculations do show that once the decision to install scrubbers for SO_x control is made, the particulate collection job should be shared by the ESP and the scrubber.

PLUME OPACITY

Theoretical calculations of in-stack light transmittance (1 minus the plume opacity) as measured by a transmissometer are inexact due to lack of data on particle refractive index and other parameters, especially the particle size distribution. However, useful estimates can be made based on the work of Ensor.[7]

The in-stack plume opacity is a function of the particle size distribution, the refractive index of the particles, the particle concentration, and the optical path length. Ensor has shown that the in-stack light transmittance is given by

$$\ln (I/I_0) = \frac{WL}{K\rho} \tag{14}$$

where I is the intensity of the light transmitted through the aerosol
I_0 is the intensity of the light source (I/I_0 is the transmittance)
W is the mass concentration of particles
L is the optical path length which is usually the stack diameter
K is a parameter which depends on the particle size distribution, the particle refractive index, and the wavelength of light
ρ is the particle density

A plot of K for a log-normal particle size distribution versus geometric mass mean radius with geometric standard deviation as a parameter for wavelength of light = 550 nm and a refractive index = 1.50 is shown in Figure 10.

The graded penetration curves for the ESP, scrubber, and ESP scrubber system can be used to estimate the log-normal parameters for various system

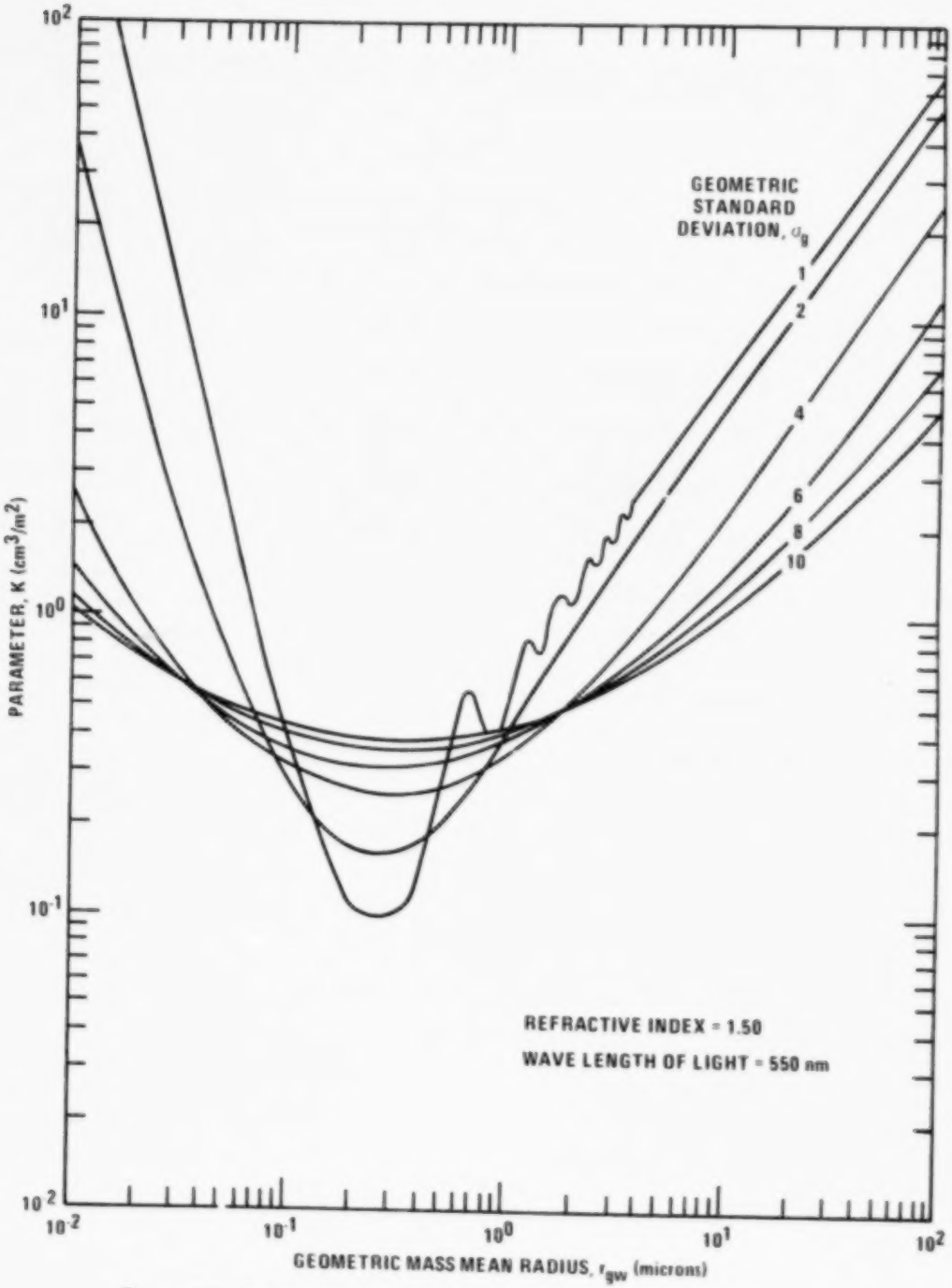

Figure 10. Parameter K as a function of the log-normal size distribution parameters for a white aerosol.

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Table 3. ESTIMATED LIGHT TRANSMISSION AND IN-STACK PLUME OPACITY FOR ESP SCRUBBER SYSTEMS

Configuration* ID Number	System	Transmission I/I_o	Opacity $1-I/I_o$
1	ESP alone	0.85	0.15
2	ESP & Scrubber	0.63	0.37
3	ESP & Scrubber	0.70	0.30
4	ESP & Scrubber	0.73	0.27
5	ESP & Scrubber	0.76	0.24
11	Scrubber alone	0.80	0.20

*Configuration ID number refers to Table 2.

All systems produce outlet emission of 13 ng/J.

configurations that meet the 13 ng/J emission limit. These log-normal parameters can then be used to estimate K from Figure 10. The light transmittance can then be calculated from

$$I/I_o = \exp(-WL/K\rho) \qquad (15)$$

We will assume $W = 0.02\ g/Am^3$ (roughly equivalent to 13 ng/J)

$L = 10\ m$

$\rho = 2.4\ g/cc$

The estimated light transmittance for each of the system configurations in Table 2 is shown in Table 3. Because the particle size distributions of the ESP scrubber system are essentially the same for both the moderate and high resistivity cases when the ESP penetration is constant, only results for the high resistivity cases are shown in Table 3.

The estimates of transmittance show that the ESP scrubber system can have considerably lower transmittance (higher opacity) than either the ESP-only system or the scrubber-only system.

It must be noted that these calculations of transmittance are subject to large uncertainties; e.g., the calculated outlet size distributions are not exactly log-normal. The ESP computer model predictions of graded penetration curves are not well confirmed with experimental data. Slight changes in the non-ideal factors in the ESP model can have a large effect on the predicted outlet size distribution, which will affect the calculated transmittance.

In spite of the uncertainties in the calculations, the fact that ESP and scrubbers operate on the particle size distribution differently will tend to make the outlet particle size distribution finer and more monodisperse. This tendency to make a fine monodisperse outlet particle size distribution should cause higher opacities for a given mass emission.

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